Transits and Photometry

The Faint Limit

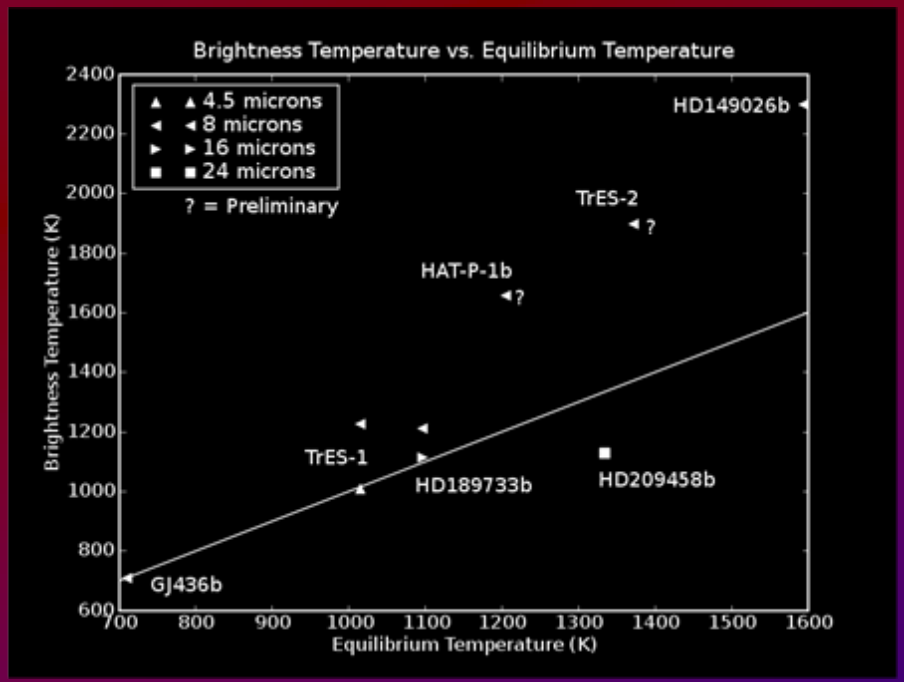
- Includes detection and characterization
- Includes transits and eclipses
- Includes phase curves and non-transiting planets (e.g., upsAnd)
- Includes broadband photometry, spectroscopy, polarimetry
- Planetary community does NOT call this large category “transits”
- Need to stop calling it “transits”

Combined-Light Measurement

The Faint Limit

Joseph Harrington

University of Central Florida

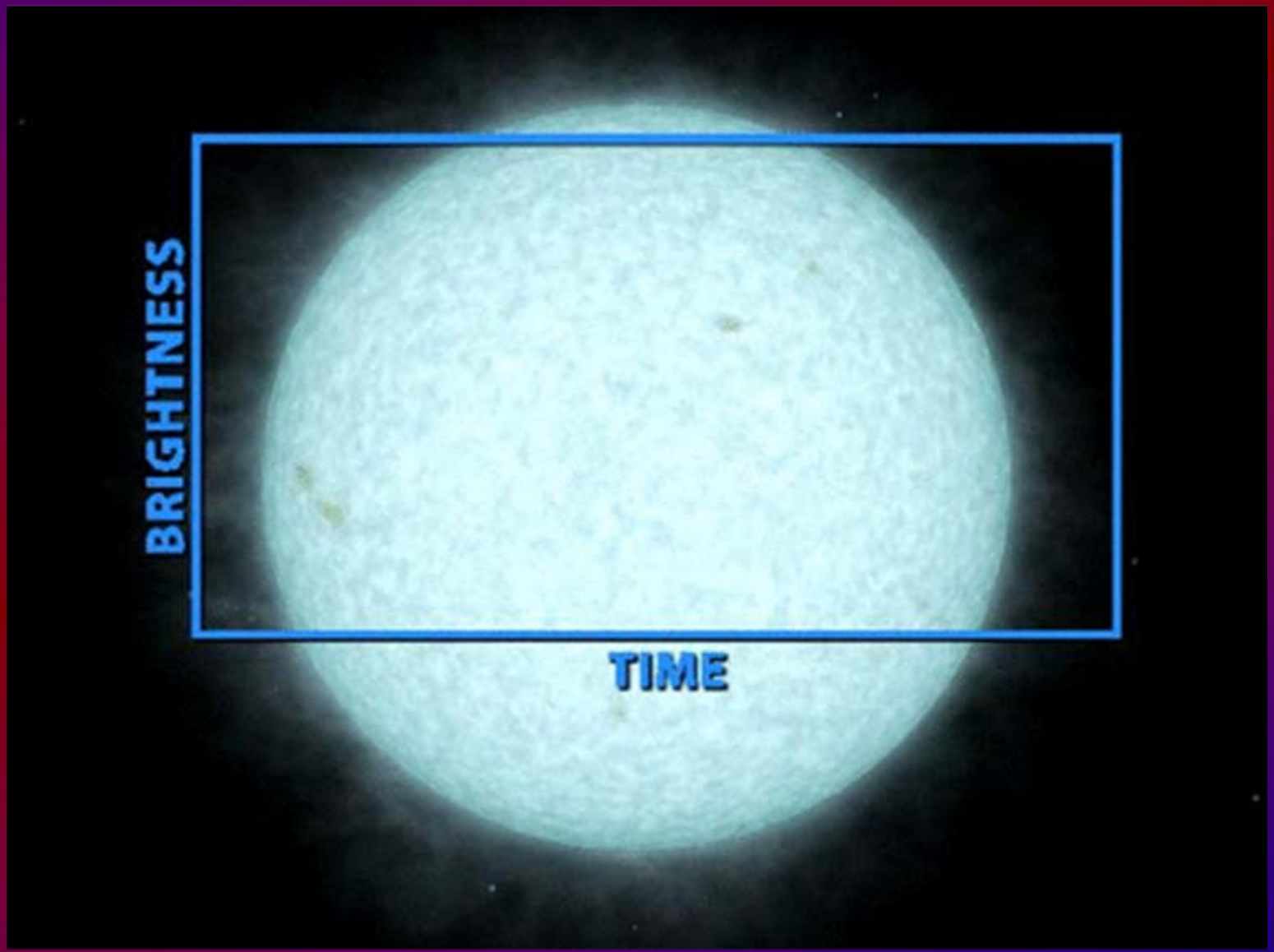


Progress in Faint Limit

- Spitzer and HST have done wonderfully on a few very bright planets, BUT:
- “Imagine how little we would know about the universe if we only had one to study.”
- Need to study as diverse a group of planets as possible
- Can't do most with spectroscopy today
- Can do many with broadband secondary-eclipse photometry

Secondary Eclipses

- If a planet transits, it usually also goes behind its star



Secondary Eclipses

Assume blackbody (Planck) emission:

$$I(\lambda) = \frac{2hc}{\lambda^3} \frac{1}{(\exp(hc/\lambda kT)-1)}$$

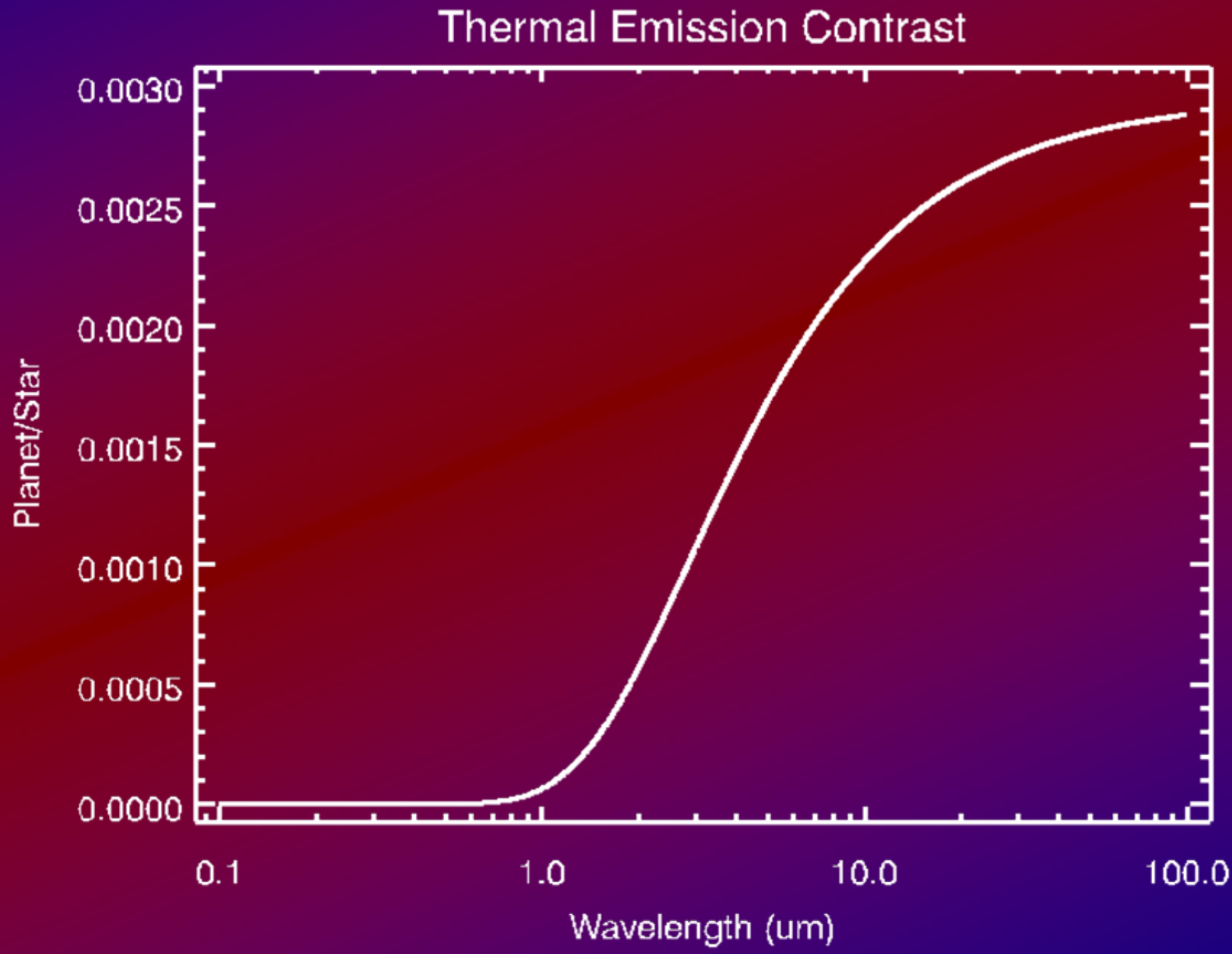
Contrast ratio, emitted light:

$$C_{\mathrm{p},\star}(\lambda) = \frac{r_\mathrm{p}^2 I_\mathrm{p}}{r_\star^2 I_\star} = \left(\frac{r_\mathrm{p}}{r_\star}\right)^2 \frac{\exp(hc/\lambda kT_\star)-1}{\exp(hc/\lambda kT_\mathrm{p})-1}$$

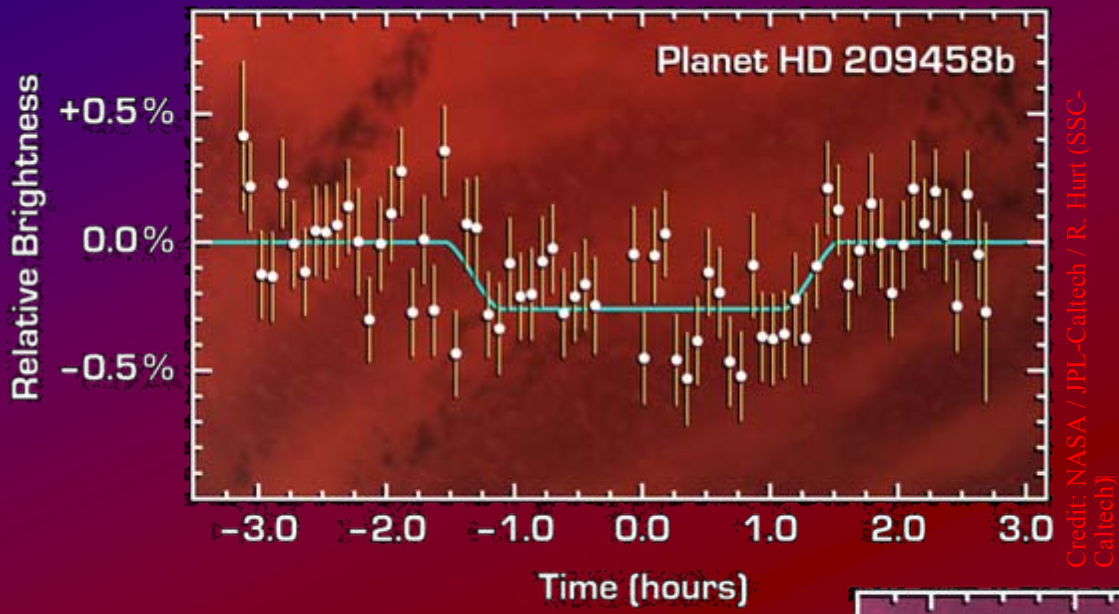
Equillibrium temperature:

$$\begin{aligned} E_\mathrm{out} &= E_\mathrm{in} \\ L_\mathrm{p} &= L_\star \left(\frac{\pi r_\mathrm{p}^2}{4\pi a^2}\right)(1-A) \\ L &= 4\pi r^2 \sigma T^4 \\ T_\mathrm{p,eq} &= \left(\frac{1-A}{4}\right)^{1/4} \left(\frac{r_\star}{a}\right)^{1/2} T_\star \end{aligned}$$

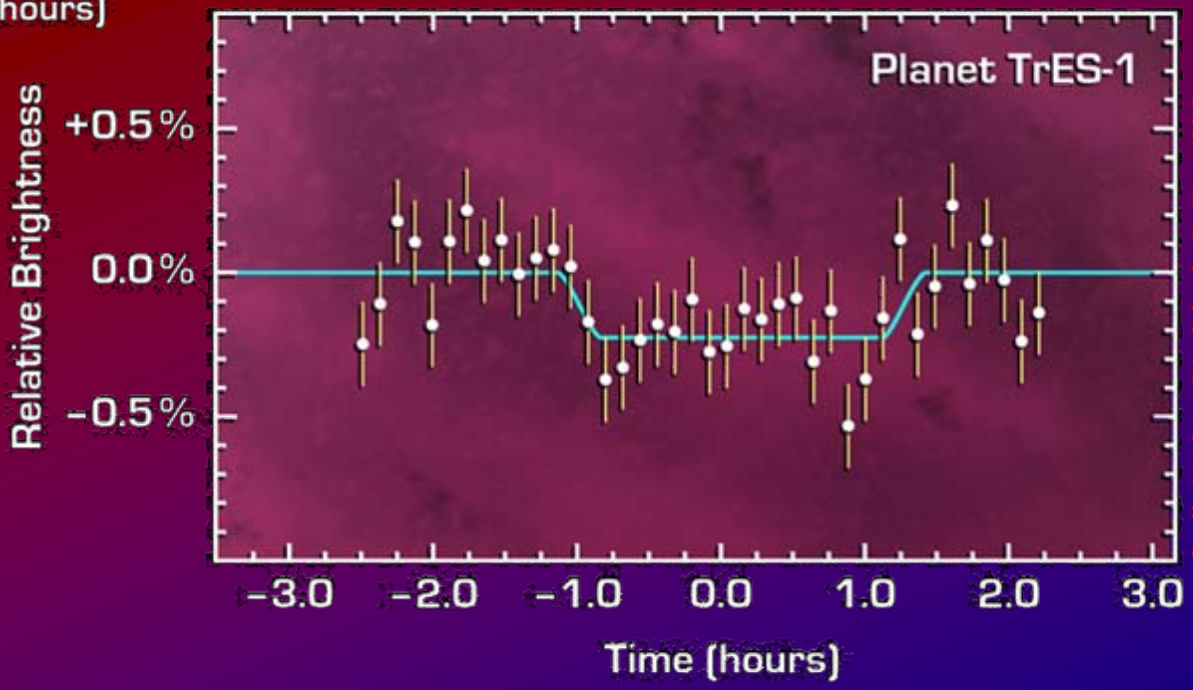
Secondary Eclipses!



First Successes

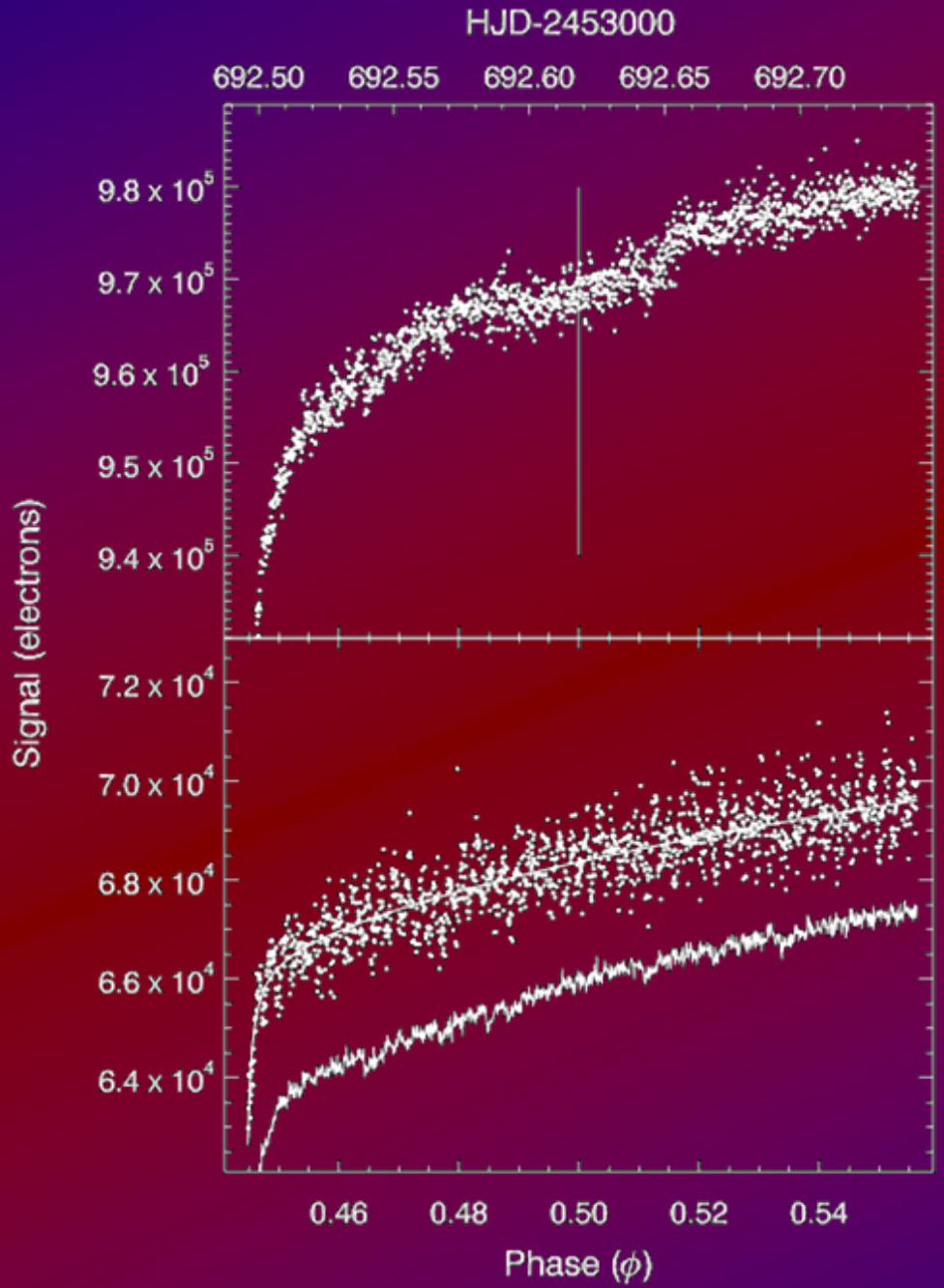


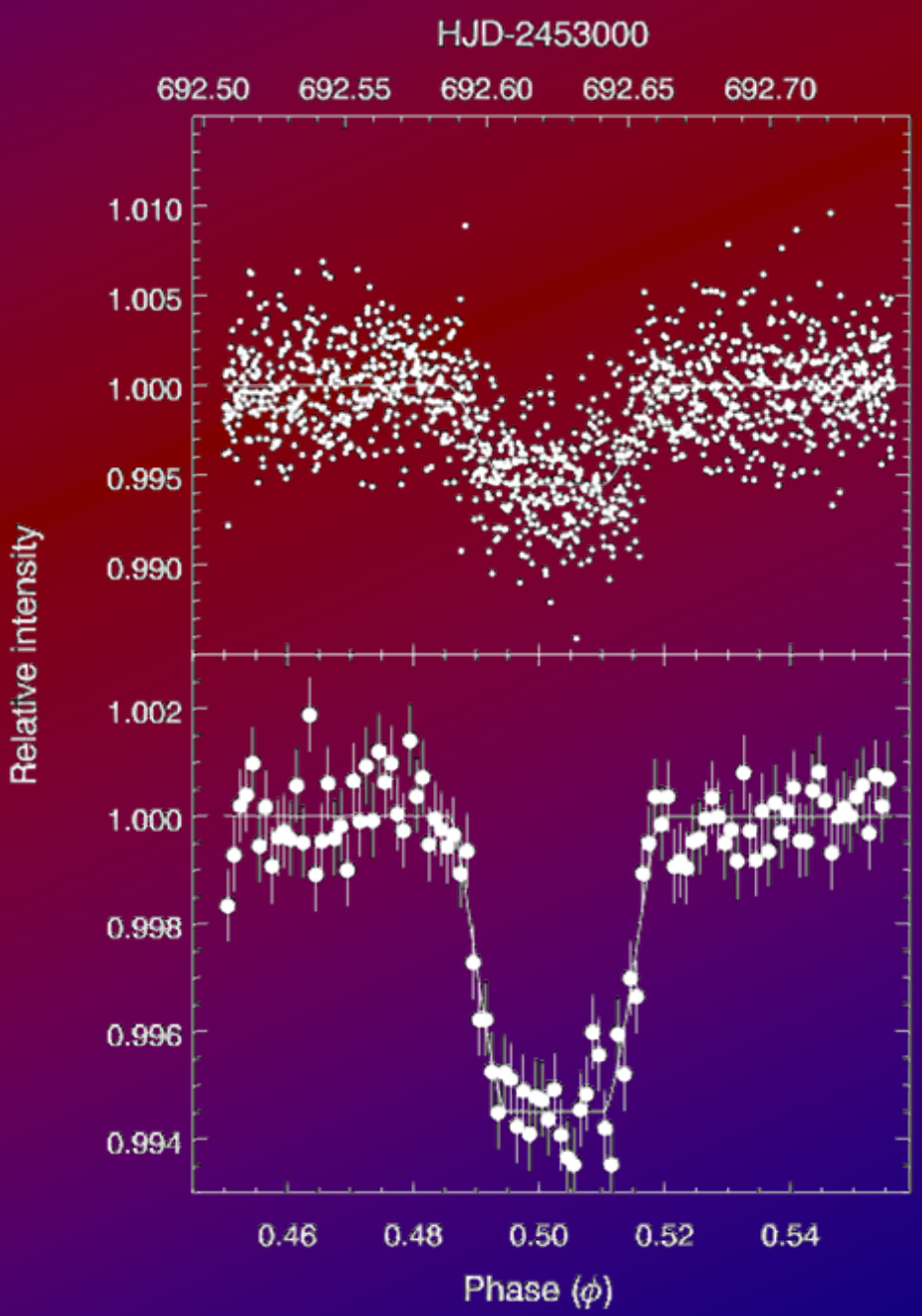
Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)



Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

HD 189733b 16-μm Data

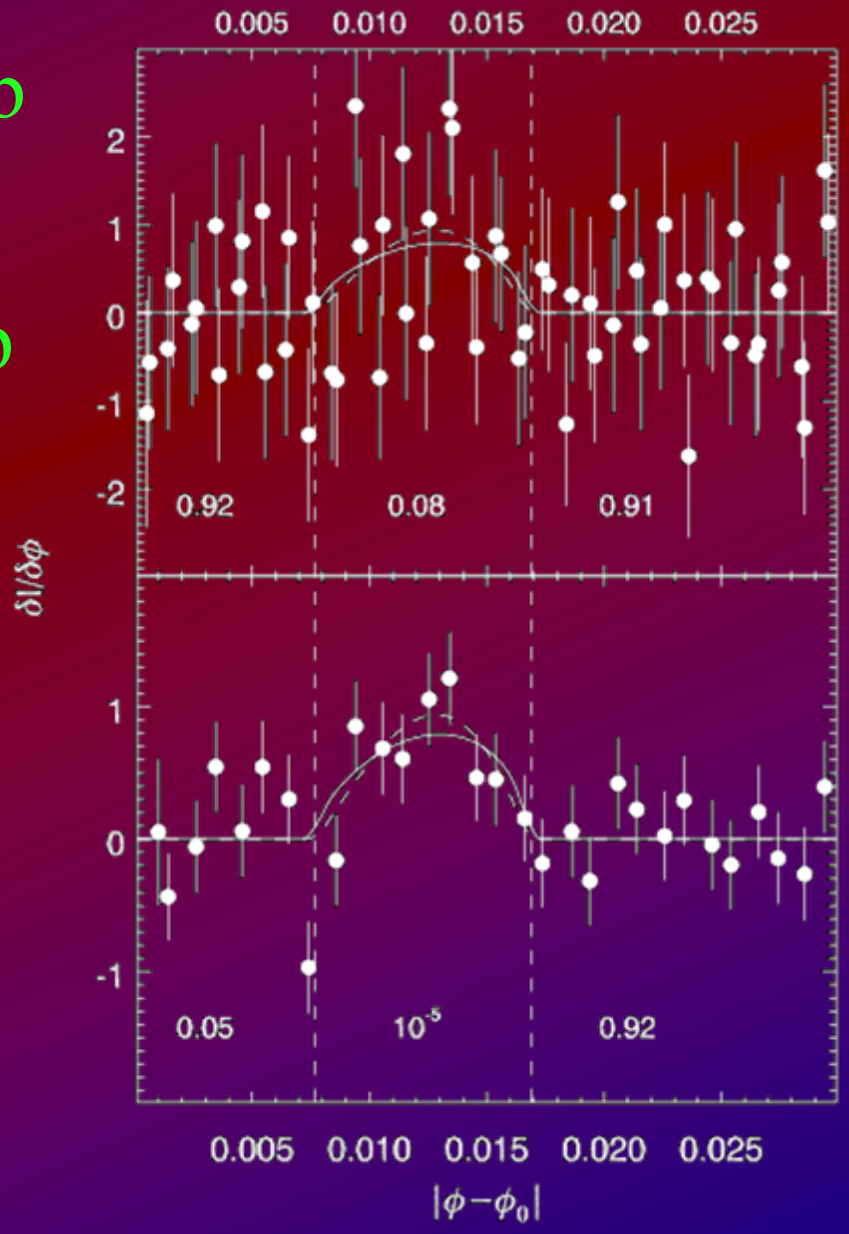




Deming *et al.* (2006, *ApJ* 644, 560)

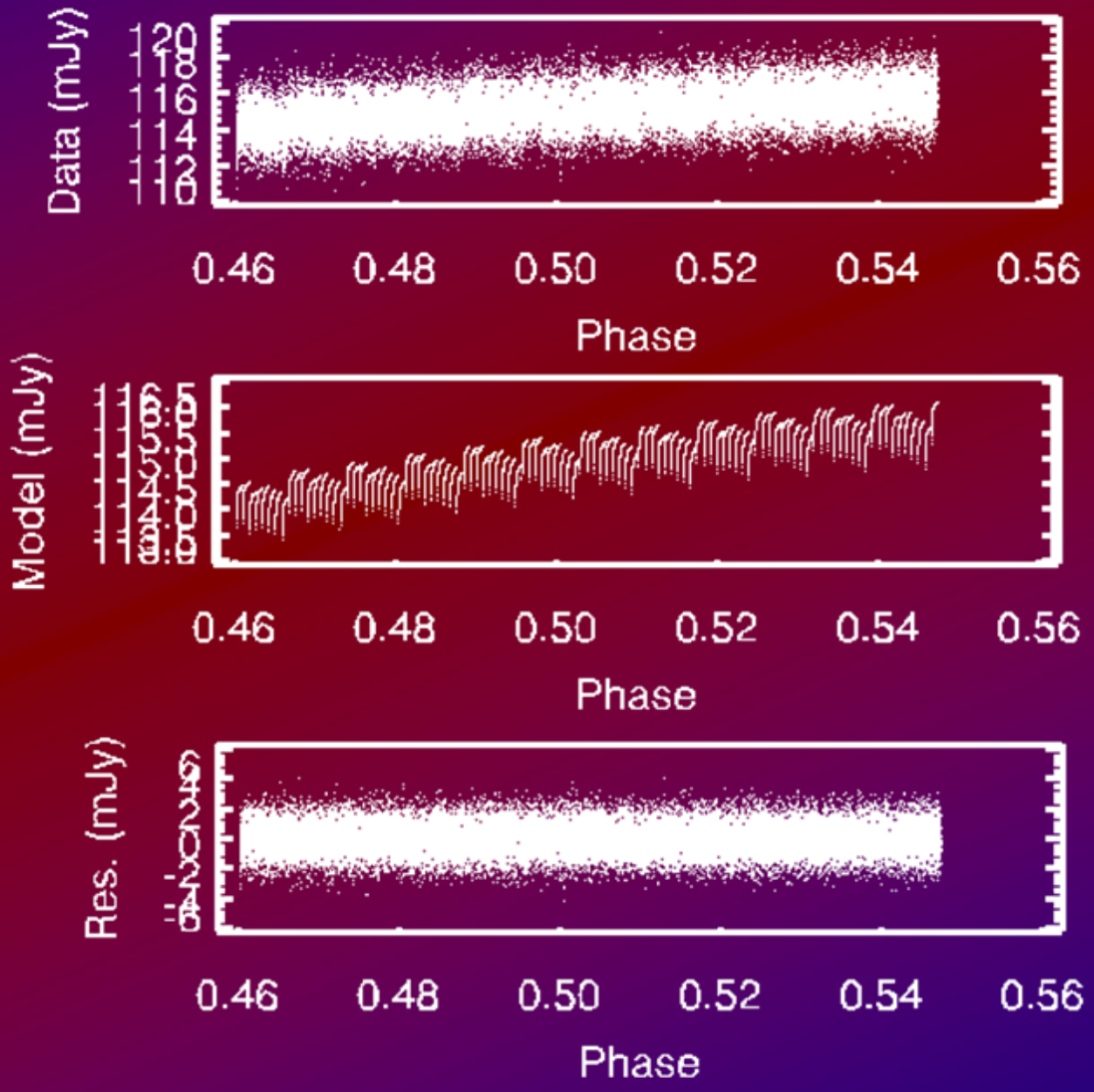
HD 189733b is round!

- Derivative of lightcurve shows planet crossing limb
- Detect that planet is round
- With better telescope, map day-side emission w/ stellar limb

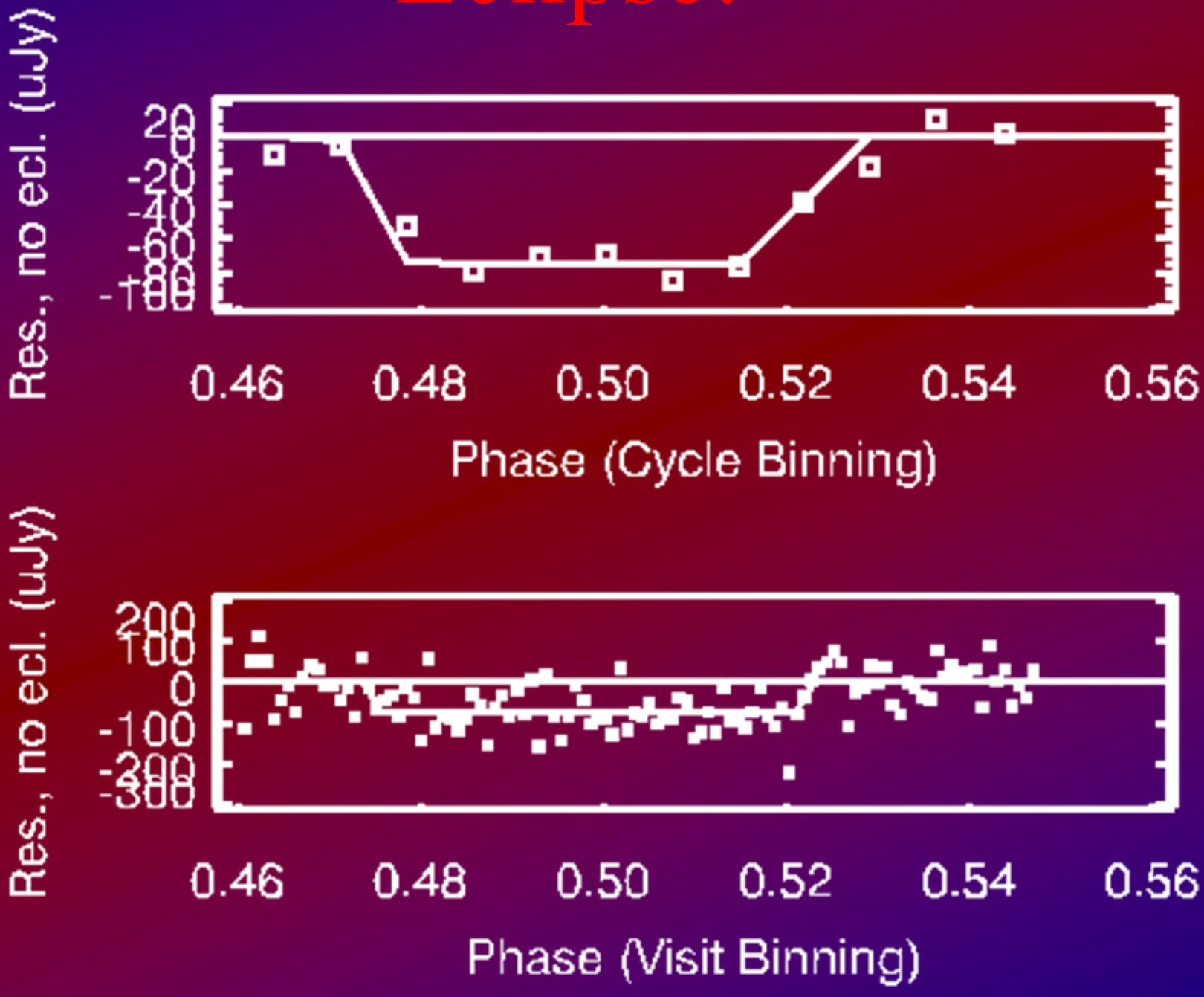


Deming *et al.* (2006, *ApJ* 644, 560)

HD 149026b


Data (mJy)
120
118
116
114
112
110
0.46
0.48
0.50
0.52
0.54
0.56
Phase
Model (mJy)
Phase
Res. (mJy)
Phase

Eclipse!


Res., no ecl. (uJy)
20
-2
-4
-6
-8
-10
0.46
0.48
0.50
0.52
0.54
0.56
Phase (Cycle Binning)
Res., no ecl. (uJy)
200
100
0
-100
-200
-300
0.46
0.48
0.50
0.52
0.54
0.56
Phase (Visit Binning)

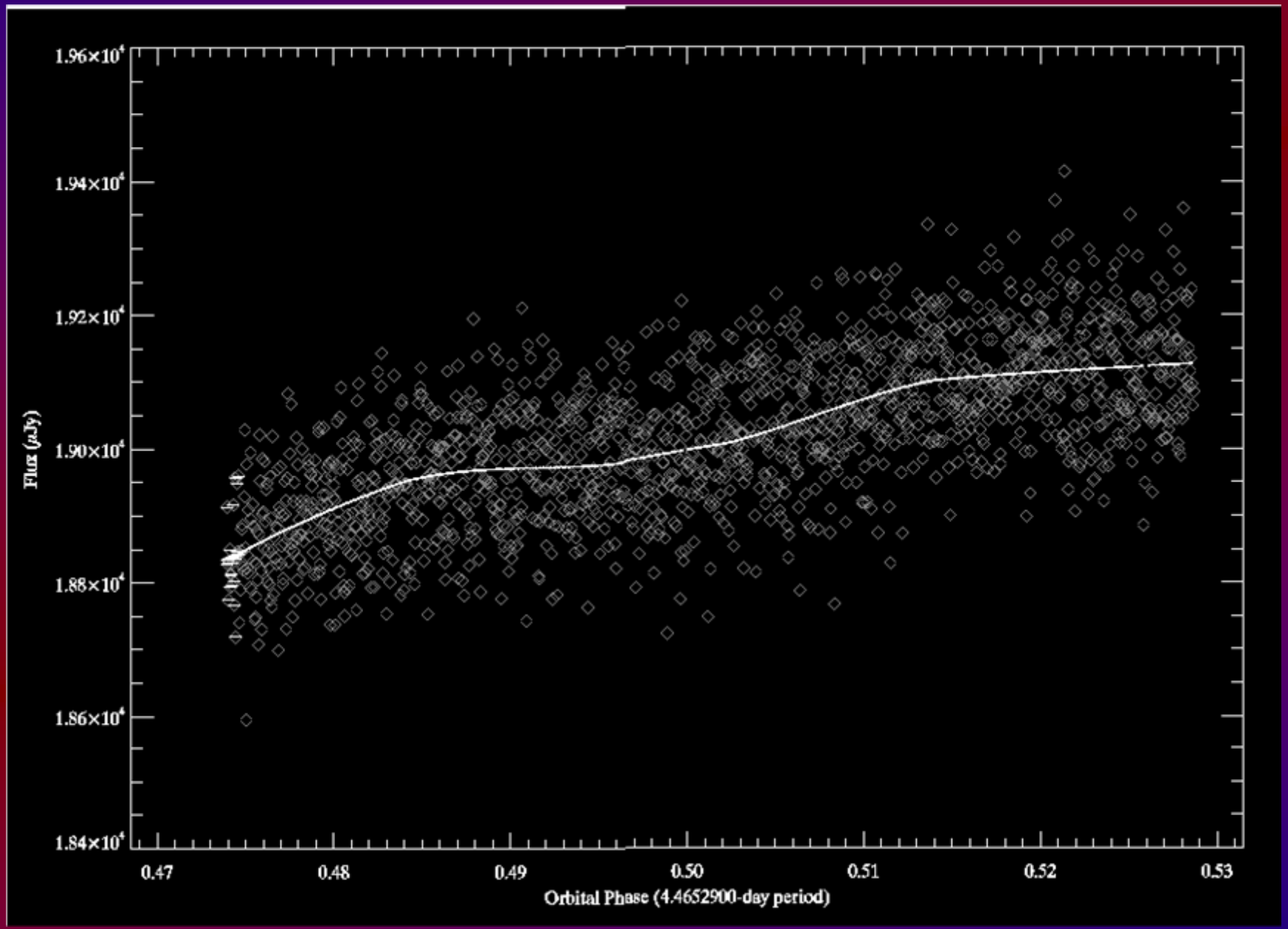
HD 149026b Results

- $F_p/F_* = 0.00084\ ^{-0.00012}_{+0.0009}$
- $T_b = 2300\ \mathrm{K} \pm 200\ \mathrm{K}$
- $T_{eq} = 1741\ \mathrm{K}$
- Kicked off theory debate about TiO/VO (Fortney *et al.*, etc.)
- Predict above a given temp that T_b should jump
- Produce atmospheric inversion
- Poor day-night energy transport

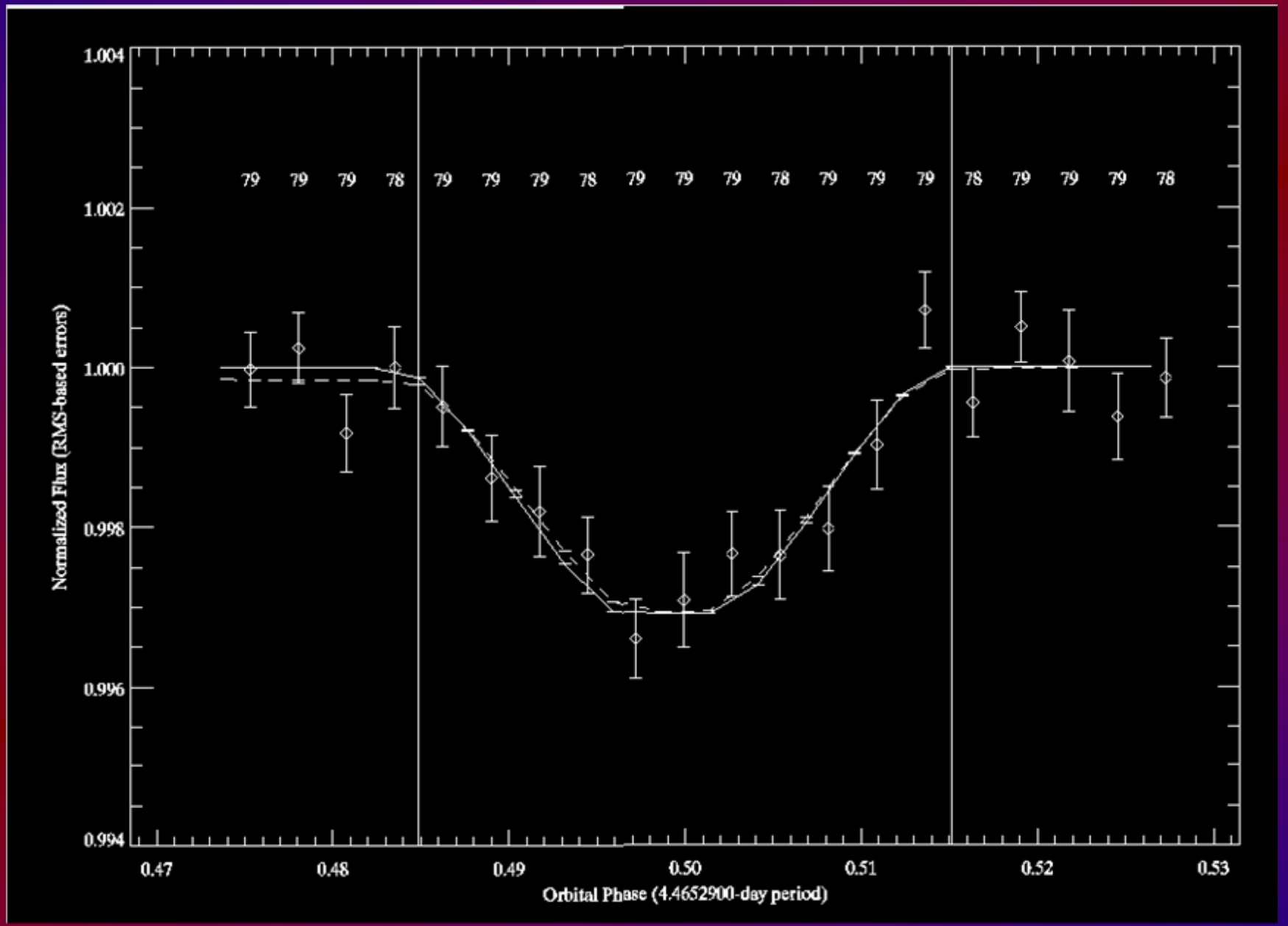
Spitzer ToO Program

- Goal: As many T_b as possible, best R
- Plentiful resources, limited cryo and human time
- Planning a *good* AOR is nontrivial – we know how
- Better to cooperate than compete
  - We work, in confidence, with all planet hunters
  - Involve discoverers in analyses of their planets
  - Work w/ discoverers on followup projects

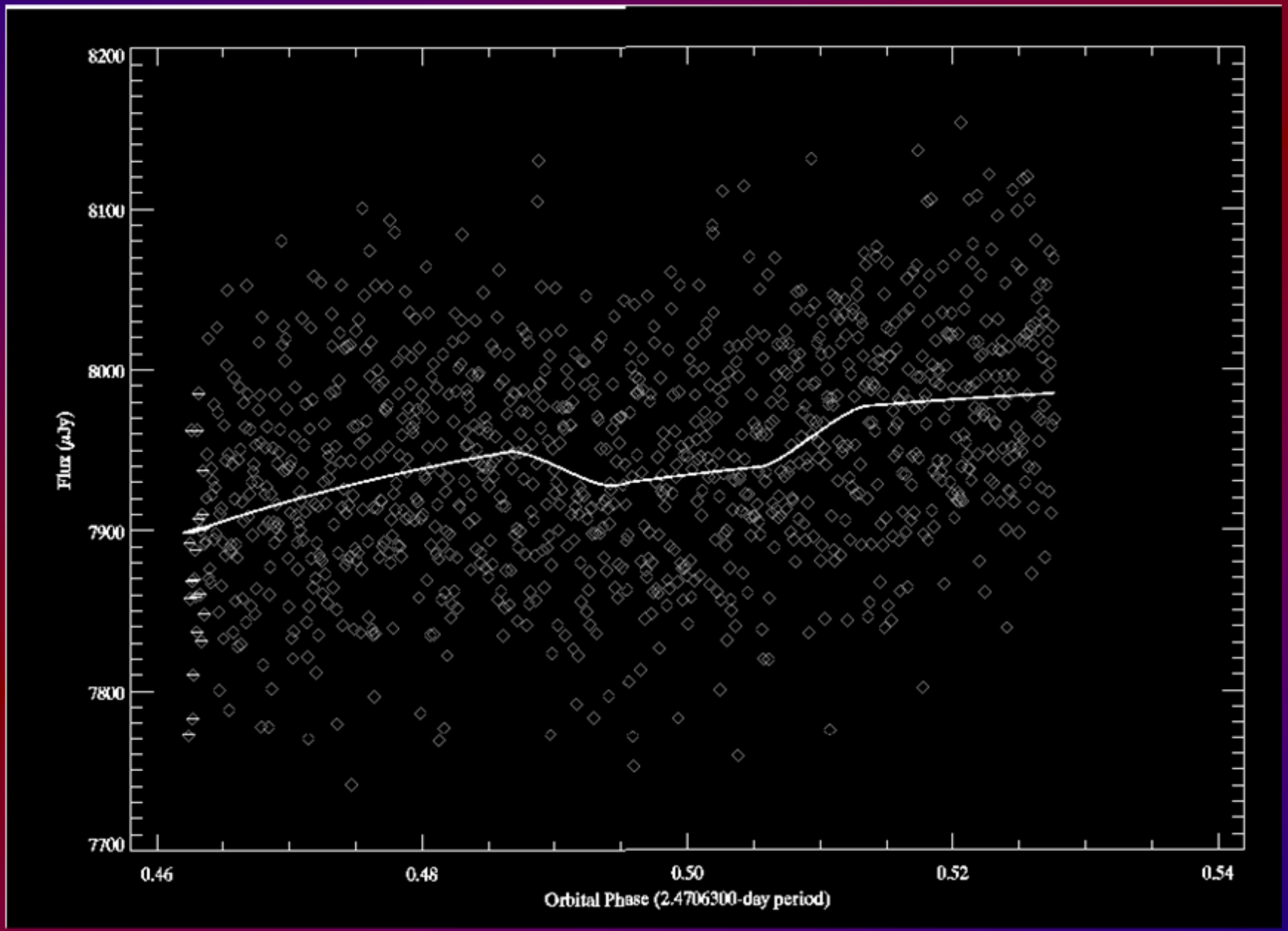
HAT-P-1b


1.96×10⁴
1.94×10⁴
1.92×10⁴
1.90×10⁴
1.88×10⁴
1.86×10⁴
1.84×10⁴
Flux (μJy)
0.47
0.48
0.49
0.50
0.51
0.52
0.53
Orbital Phase (4.4652900-day period)

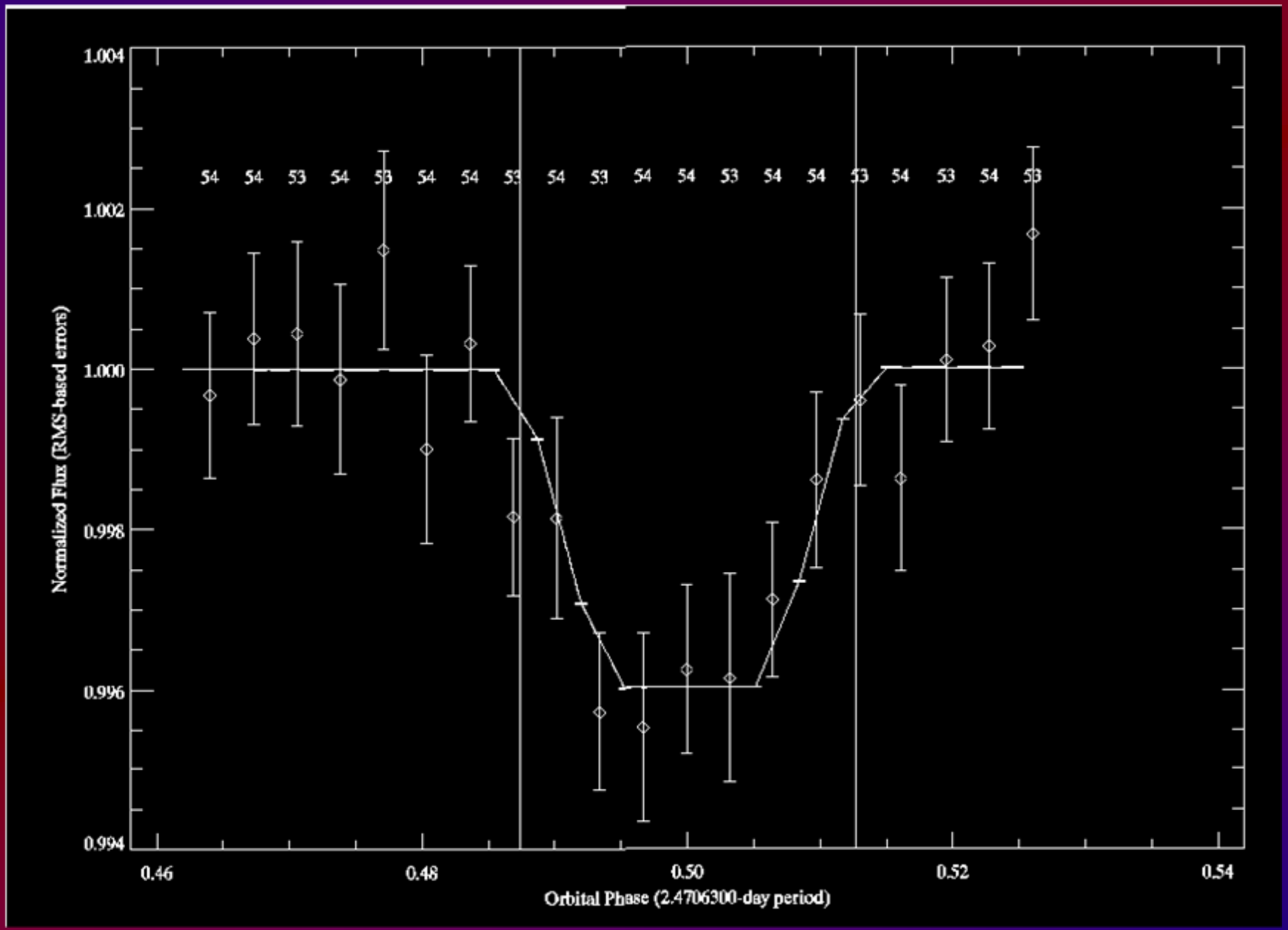
HAT-P-1b


1.004
1.002
1.000
0.998
0.996
0.994
Normalized Flux (RMS-based errors)
79 79 79 78 79 79 79 78 79 79 79 78 79 79 79 78 79 79 79 78
0.47
0.48
0.49
0.50
0.51
0.52
0.53
Orbital Phase (4.4652900-day period)

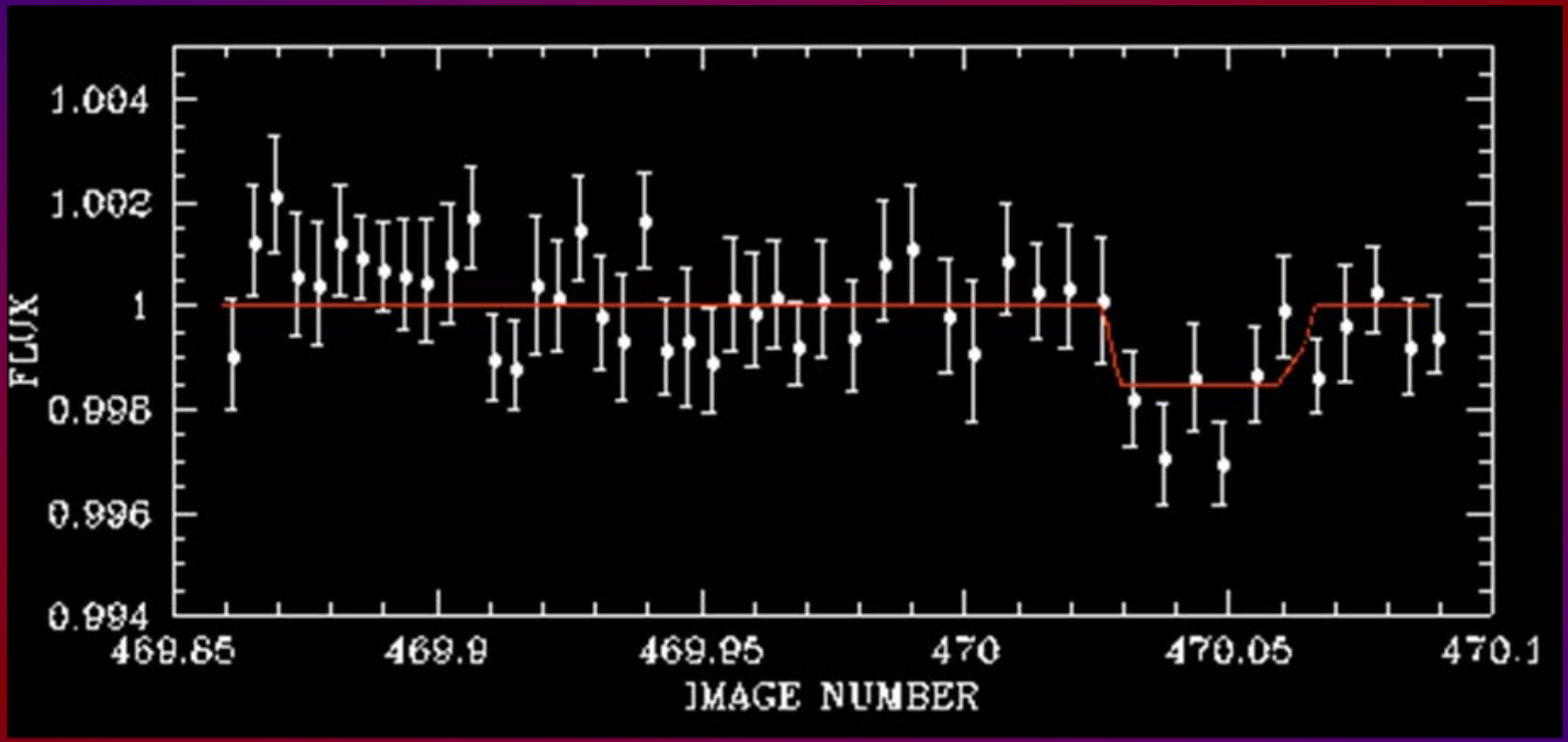
TrES-2


8200
8100
8000
7900
7800
7700
Flux (μJy)
0.46
0.48
0.50
0.52
0.54
Orbital Phase (2.4706300-day period)

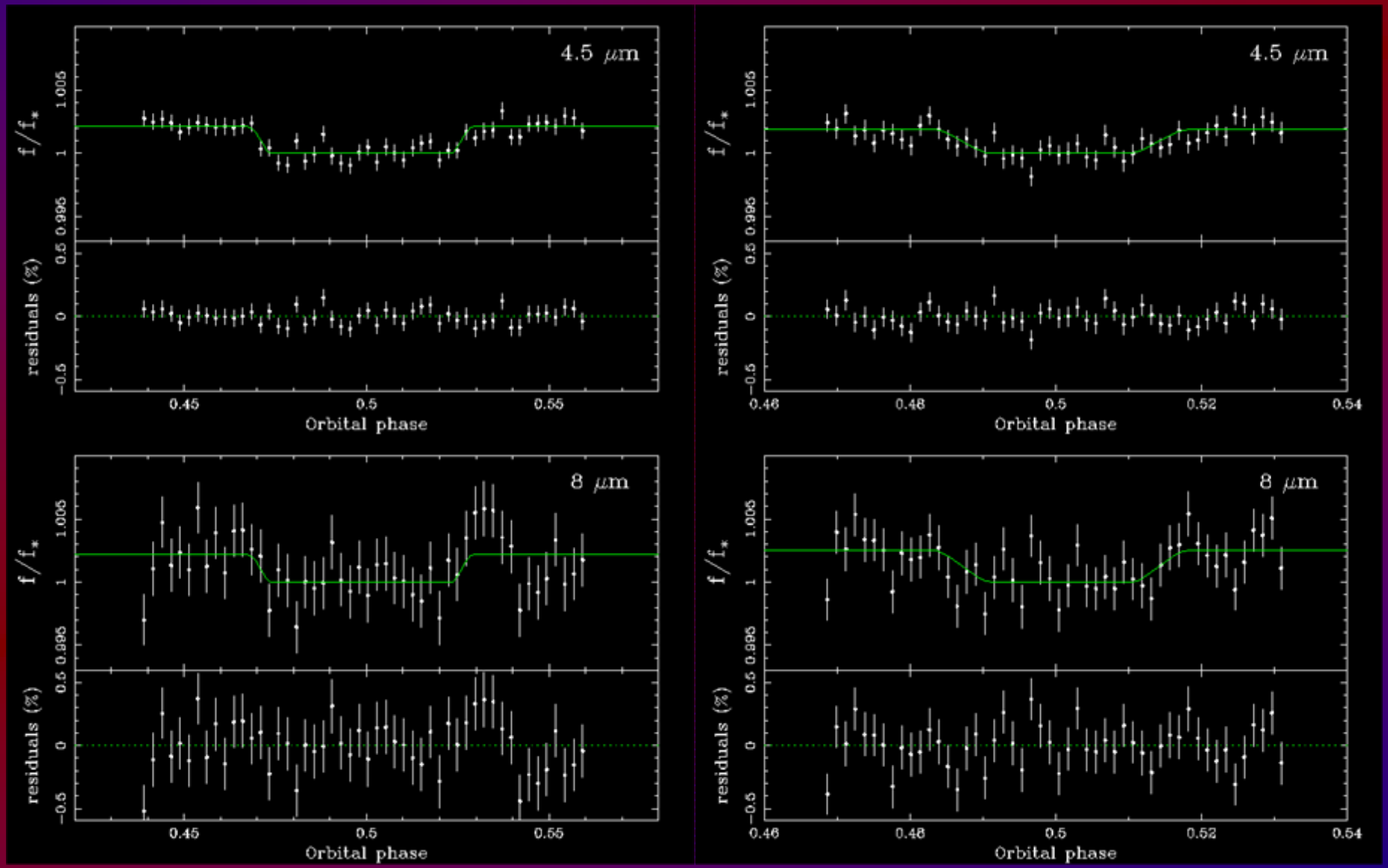
TrES-2

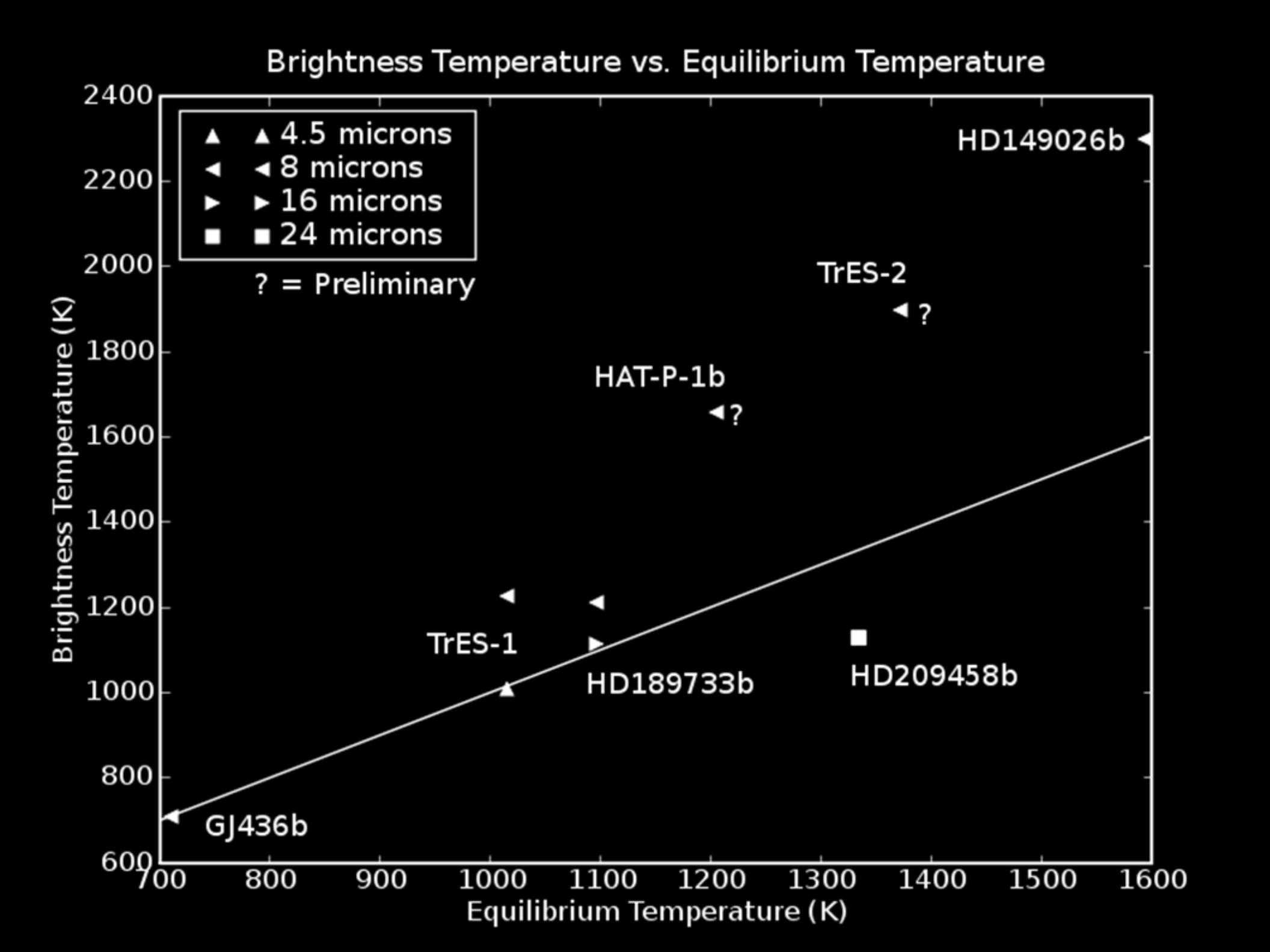

1.004
1.002
1.000
0.998
0.996
0.994
Normalized Flux (RMS-based errors)
54 54 53 54 53 54 54 53 54 53 54 54 53 54 54 53 54 53 54 53
0.46
0.48
0.50
0.52
0.54
Orbital Phase (2.4706300-day period)

GJ436b 24 um


1.004
1.002
1
0.998
0.996
0.994
FLUX
469.85
469.9
469.95
470
470.05
470.1
IMAGE NUMBER

WASP-1b and -2b




Brightness Temperature vs. Equilibrium Temperature
4.5 microns
8 microns
16 microns
24 microns
? = Preliminary
HD149026b
TrES-2
?
HAT-P-1b
?
TrES-1
HD189733b
HD209458b
GJ436b
Brightness Temperature (K)
Equilibrium Temperature (K)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
700
800
900
1000
1100
1200
1300
1400
1500
1600

Technical Lessons

- We are looking at dim next to bright
- The systematics are *everything*
- This is unlike most prior spacecraft science
- Can't assume you can fix systematics after the fact
- Calibrate! Either on the ground or fly it
- Stability over weeks/months valuable
- Things moving fast: far-out mission plans may be obsolete before flown!
- Take small steps quickly, or risk flying limiting instrument on flagship mission

Characterization Mission

- Goal: Spectral phase curves to measure molecules
- Include transits, eclipses, best non-transiting
- Super-Earths on M-dwarfs
- Warm/Hot Jupiters on solar-type stars
- Spitzer-like design (panel is sunshield)
- 1-2 meter telescope
- No cryogen
- Orbit allows long stares, thermal stability
- Super-stable pointing

One Instrument

- High-throughput, medium-res, single-setting spectrograph
- 0.7-few μm, get H_2O, CO, CO_2, CH_4, H_3^+, NH_3, etc.
- Possible externally dispersed aperture for high res
- Broadband filter apertures chosen for **molecules**
- Integrating sphere puts calibration into each frame
- No internal reflections
- Rock-stable over weeks/months

Benefits

- 3-10 planets: high-level spectroscopy around orbit
- 50-200 planets: broadband secondary eclipses
- 3-10 planets: repeated eclipses/transits
  - Variability: chemical weather
  - Transit timing search for perturbers
  - Limb-crossing dayside maps!
- Long, continuous views, 100s of hours
- No new technology, fly it now
- Cheap, probe-scale mission